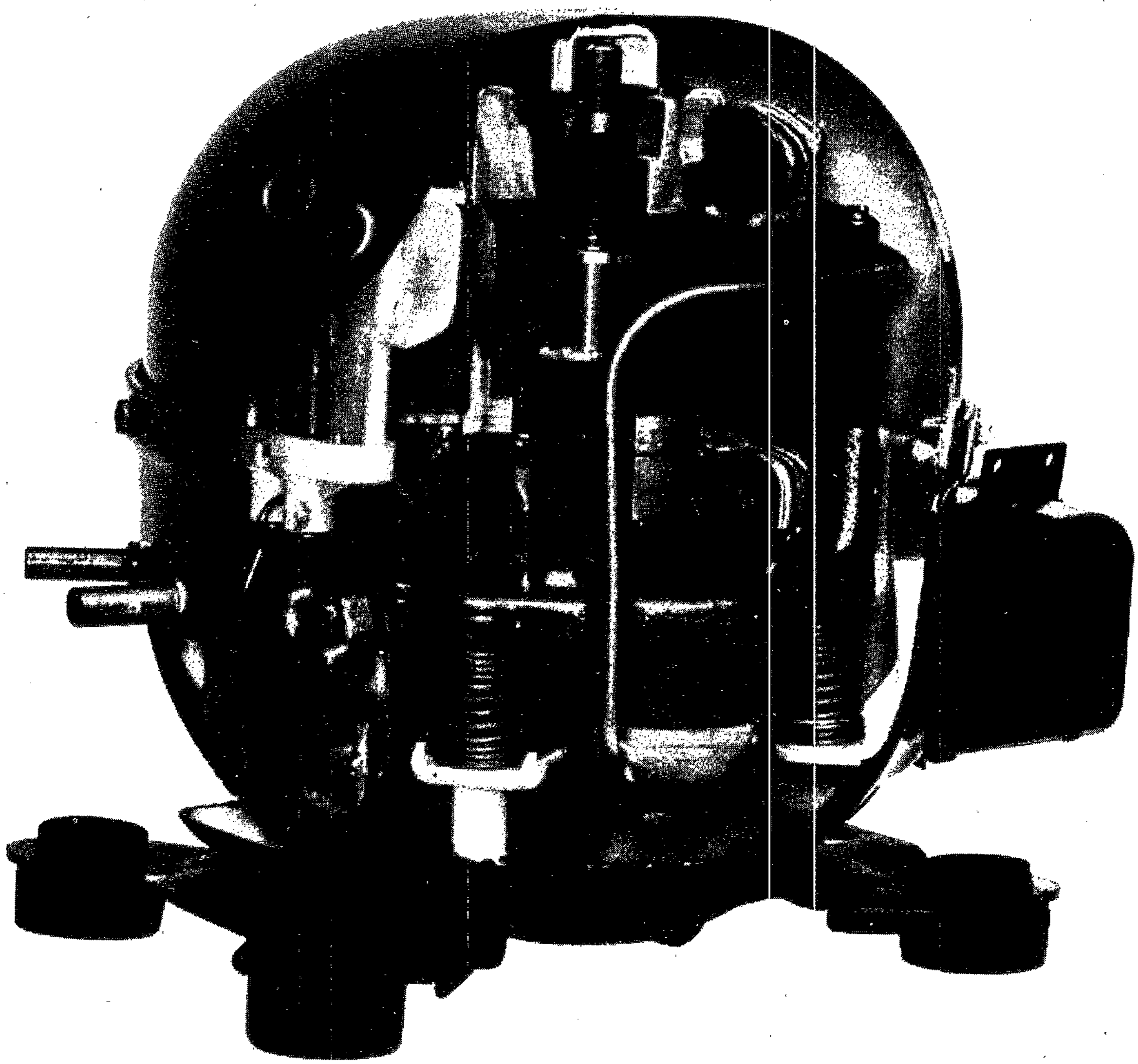
United States
Environmental Protection
Agency

Office of Atmospheric
and Indoor Air
Programs

EPA-430-R-93-009
June 1993

EPA

# State of the Art Survey of Motor Technology Applicable To Hermetic Compressors For Domestic Refrigerator/Freezers



# State Of The Art Survey Of Motor Technology Applicable To Hermetic Compressors For Domestic Refrigerator/Freezers

Prepared for
Environmental Protection Agency
Division of Global Change

Revised: March, 1993

Reference 64128
64122
67986

## Prologue

Motor technology can play an important role in allowing potential efficiency improvements of various refrigerator/freezer design alternatives. This review of the motor technology applicable to small hermetic refrigeration compressors was undertaken as part of a larger study to evaluate the options for maximizing the efficiency of domestic refrigerators. The motor characteristics documented in the report are being used in the overall study as part of the input database for modeling and evaluating design options.

## Findings

1. ***Two kinds of approaches are possible for compressor motors.***

- Constant speed, 2 pole, 115 VAC, 60 HZ, single phase, squirrel cage induction motors are current practice in all refrigerators and freezers; motor speed is close to 3500 RPM;

- Variable speed alternatives are:
  - 2 speed (1750/3500 RPM) squirrel cage induction motors; and
  - Continuously variable speed, electronically driven motors.

2. ***Smaller compressors will be needed in future refrigerators.***

- super insulation (either vacuum panels or thicker walls) is likely to reduce loads.

- Dual loop (or staged) systems using two compressors may replace single compressor/evaporator designs to gain theoretical energy efficiency advantages.

3. ***Small compressors are inefficient because of inefficient motors; these can be improved with currently available technology.***

- Current small compressors are relatively inefficient, mainly due to inefficient motors.

- Current technology exists to make efficient motors for small compressors at a reasonable price.

4. ***Variable speed technology can provide an additional and/or alternative means to achieve superior energy efficiency***

- Variable speed compressor operation has the potential to reduce compressor power requirements by virtue of more efficient heat exchanger utilization and elimination of cycling losses.

- Two speed induction motors are a low first cost, relative to electronically driven variable speed motors, means of reducing compressor on/off cycling.

- Two speed motors, though not currently produced for or used in domestic refrigerator compressor applications, could be produced for this application, at a cost approximating that of premium efficiency single speed motors, but at an efficiency reduction of 5% at full speed and close to 15% at half speed. At these reduced motor efficiency levels, no net improvement in R/F energy consumption can be expected to result from their use.

- The most efficient small variable speed motor/drive system alternative is an electronically commutated permanent magnet rotor DC motor, with full speed system efficiency comparable to the best single speed induction motor, and half speed efficiency within a few percent of full speed. There is some uncertainty with respect to the cost level that would be reached after a few years of mass production, but one quarter horsepower ECM motor/drive systems are currently being produced and sold on a modest scale OEM basis for approximately $100.

- OEM unit costs of these variable speed drives could fall to $50-$55 (or less) in large scale (hundreds of thousands of units annually) mass production.

- The variable speed drive and motor can operate at higher speeds, allowing reduced compressor cost, and replaces the existing compressor motor, for offsetting cost reductions of approximately $20. The net increase in OEM component costs, then, would be approximately $30-$35.

- Modeled results of R/F performance with a variable speed compressor show improvements in performance over a single speed compressor.

- A substantial energy saving (10%) can be obtained by replacing the inefficient fan/motor of typical current practice with a modest efficiency fan and motor.

- With the standard efficiency fan/motor, the variable speed drive operating at steady state results in increased total energy, with the energy associated with 100% fan run time more than offsetting compressor power savings.

- With efficient fans, the VSD compressor shows energy savings.

- With variable speed fans added to the VSD, substantial energy savings are obtained.

- A limitation on the compressor energy savings is the declining variable speed motor system efficiency below half speed.

- The same general observations apply to the application of VSD to a high performance cabinet, with increased sensitivity of the variable speed options to the fan efficiency.

- The value of these energy savings was calculated. Assuming an electric energy cost of 8¢ per kWh, for real discount rates less than 10% the real, present value of the saved energy is on the order of $75, over the projected 15 year life of the refrigerator, greater than the incremental cost, of the variable drive.

5. ***Energy improvements from improved compressor performance, especially small compressors, are possible with improved motors and variable speed technology. Dual loop and super-insulation systems should be economically viable with this currently available (but as of yet) unmanufactured technology.***

- Motors for small compressors can be improved to efficiency levels within a few percent of large compresors for $15, while the energy gain they would produce would be worth $75.

- Variable speed technology could add $35 (costs) to refrigerators, but save more than $10 per year in electricity.

- Research and improved manufacturing could improve the benefit/cost calculations used in this report.

## Table of Contents

## Table of Figures



## Table of Tables

## Acknowledgements

During the course of this work, a number of compressor, motor, and variable speed drive manufacturers were contacted, whose assistance and cooperation we acknowledge and appreciate:

- Compressors: Tecumseh Products Co., Copeland, and Americold
- Motors: General Electric, A. O. Smith, Emerson, and Baldor
- Variable speed drives: Toshiba, Emerson, Mitsubishi, Hitachi, Westinghouse, Magnetek, Lenze, Vee Arc, Ranco, Inland, PMI, Minarik, EG&G, Fasco, Boston Gear, and Graham

# 1.0 Introduction

The design of the domestic refrigerator-freezer will be undergoing a significant set of changes over the next several years, driven by interrelated developments in a number of national energy and environmental policy areas - the CFC phase out, growing concerns about global warming, DOE appliance energy efficiency standard setting, and others. These developments have created the need for a comprehensive examination of the design options for domestic refrigerator/freezers. These interrelated options include compressors, motors, refrigerants and lubricants, the refrigeration cycle, cabinet insulation, and other aspects of cabinet thermal design.

This report covers the technology status of the motors that are used, or potentially could be used, in the small hermetic compressors used in the refrigeration system of domestic refrigerators, addressing the potential for and cost of improvements in the efficiency of these motors. The status of applicable variable speed motor technology and potential refrigerator energy savings is examined.

The environmental and energy policy background is discussed briefly below.

## 1.1 Stratospheric Ozone Depletion and the CFC Phase Out

Evidence accumulated over the past 15 years indicates that fully halogenated chlorofluorocarbons (CFCs) have caused measurable deterioration of the atmosphere's stratospheric ozone layer, which plays a significant role in attenuating solar ultraviolet radiation. Increased levels of ultraviolet radiation would have a large number of undesirable effects, including increased levels of skin cancers. Over the past few years, this subject area has received renewed attention as the result of observations in the mid-1980s of "gaps" in the ozone layer in the vicinity of the poles. As a result of this attention, the Montreal CFC protocols were concluded in Fall, 1987. This international agreement was signed and ratified by the major free world industrial nations requiring a freeze, then phased production curtailments, of CFCs. By 1998, production of CFC-11, CFC-12, CFC-113, CFC-114, and CFC-115, as well as certain "halons" were to be reduced to 50% of 1986 levels. An additional provision provided for periodic review of scientific evidence and adjustment of allowable levels of production accordingly. The reassessment completed in 1990 resulted in a nearly total phase out of CFCs by the year 2000. The Clean Air Act of 1990 has codified this accelerated CFC phase out schedule into U.S. environmental law. In April of 1991, NASA reported the results of satellite-based measurements of stratospheric ozone levels indicating that ozone depletion of 5% over the mid latitudes has already occurred. The likely result of this development will be further acceleration of the timetable for CFC phase out. This has a direct impact on R/F insulation and compressors which have been designed around the characteristics of CFC-11 and CFC-12, respectively.

## 1.2 Global Warming

Concurrent with the accumulation of scientific evidence of stratospheric ozone depletion, increasing concerns have been developing about global warming caused by increasing atmospheric concentrations of carbon dioxide and the trace greenhouse gases. The most significant of the trace greenhouse gases are the CFCs and methane.

The fact that the CFCs are powerful greenhouse gases has reinforced the pressures to accelerate the CFC phase out time table. Measures to limit or reduce $CO_2$ emissions have been proposed. Because $CO_2$ is one of the basic combustion products of all of the fossil fuels used to produce energy for heating, transportation, and electric power generation, measures to reduce $CO_2$ emissions require the burning of less fossil fuels. One regulatory measure to bring this about is increasing energy efficiency standards.

## 1.3 DOE Appliance Energy Efficiency Standard Setting

In February, 1989, DOE issued a final rulemaking under the Energy Policy and Conservation Act, as amended, establishing minimum energy efficiency standards for most categories of consumer appliances (Federal Register, 1989a). Depending on the category, the standards take effect between 1990 and 1993. The standards for domestic refrigerators and freezers went into effect on January 1, 1990, generally requiring efficiency levels in line with the most efficient products available in the late 1980s, whose efficiency was nearly double the levels prevailing only 10 to 15 years earlier.

Global warming (and national energy security issues) have resulted in the recent adoption of significantly reduced levels of allowable electric energy consumption for all categories of domestic refrigerators and freezers, effective on January 1, 1993 (the 1993 standards reduce allowable energy consumption by approximately 30% from the levels under the current Federal regulations that took effect on January 1, 1990) (Federal Register, 1989b).

## 1.4 Other Regulatory and Policy Initiatives

States are instituting reforms in planning and rate making that put demand reductions on an equal playing field with building additional supply capacity. Integrated resource planning, adopted by many states, requires utilities to evaluate every "resource" (demand reduction or supply) in terms of total societal cost.

California, Oregon, Washington, most of the New England states, Wisconsin, and New York have adopted ratemaking processes in which utility rates or return on investment is adjusted so that utilities do not lose profits for forgone Kwh sales, but can profit from demand reductions. In California and several other states, the non-pollution aspect of demand reductions has led regulators to allow shared savings of customer bill reductions to further increase utility profits. As a consequence of this change in utility regulation, the demand for efficient refrigerators is rising.

The Golden Carrot/early retirement program is one concrete manifestation of this trend. Under the Golden Carrot, utilities are banding together to pool rebates to produce an incentive for production of a R/F that is 30% better than DOE's 1993 standard in the 18 to 22 cubic foot range. With the impetus described earlier from CFCs, global warming, and other state regulatory reforms, the Golden Carnot will provide a strong incentive for vast improvements in energy efficiency.

## 2.0 Issues in Compressor and Motor Selection

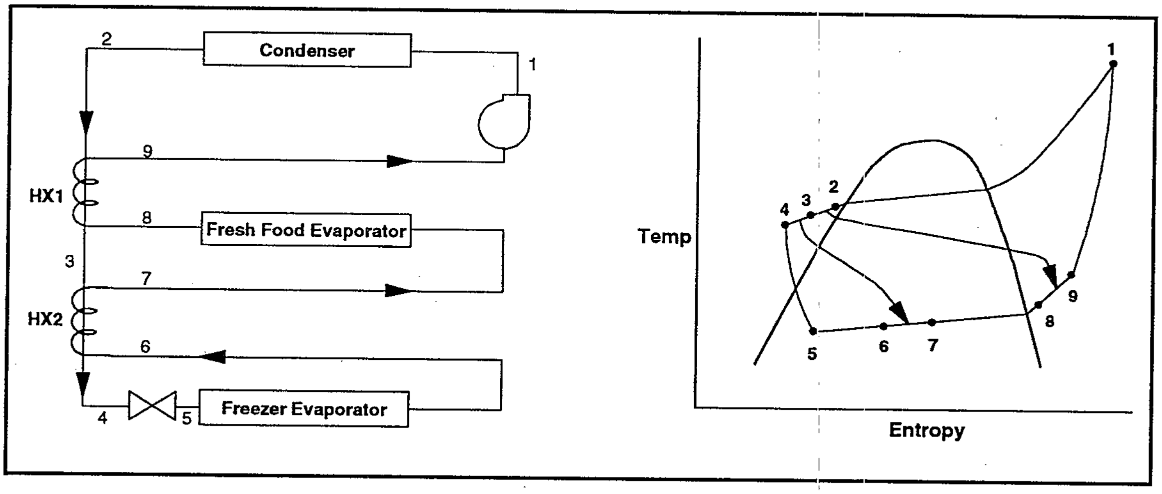
To meet the dual challenge of designing for new blowing agents and refrigerants, while meeting much higher efficiency standards, significant changes in the design of both the cabinet and the refrigeration cycle are under consideration. There are many design options, and it is important to evaluate the potential of each option to contribute significant energy savings, without using CFCs and without increasing the cost of the refrigerator beyond the value added by the change (with respect to energy costs or utility) or decreasing the utility of the refrigerator to the consumer. Design options that are being pursued in current R&D programs include:

- Low thermal loss cabinets ("super-insulated boxes") reduce energy consumption by reducing the amount of cooling that is needed. To utilize heat exchangers effectively and minimize cycling losses, the compressor capacity should be reduced in proportion to the thermal load. However, sufficient compressor capacity may still be required to provide a sufficiently fast pulldown for food preservation.

- Dual refrigeration loops (separate refrigeration systems for the refrigerator and freezer compartment) take advantage of the increased COP at the higher evaporator temperature that can provide the required cooling of the fresh food compartment.

- The Lorenz cycle, shown schematically in Figure 2-1 uses a non-azeotropic refrigerant mixture with two evaporators and an interchanger to operate the fresh food compartment and the freezer at separate evaporator temperatures for higher efficiency. (Lorenz, 1975)

**Figure 2-1: Lorenz-Meutzner Refrigerator/Freezer Cycle**




- Variable speed compressor operation can save energy by allowing continuous operation at low capacity, eliminating cycling losses and allowing more efficient utilization of heat exchangers. Overspeed operation can provide additional capacity for pulldown. The latter characteristic might be particularly advantageous with high performance cabinets.

One consequence of these design changes is a decrease in the compressor capacity required to best match a given size refrigerator. Improved insulation and cabinet design will reduce cooling loads, reducing required compressor capacity. Two compressor/two evaporator systems meet the freezer and fresh food compartment heat loads with separate refrigeration systems, obtaining, in theory, significant improvements in the efficiency with which the load in the fresh food compartment is met (higher evaporating temperatures, no defrost cycle). Even less compressor capacity is needed, especially in the fresh food compartment where nominal compressor capacities of only 200 Btu/hr may be needed. While the Lorenz cycle does not inherently result in a drastic compressor capacity reduction, other compressor problems, such as high starting torque requirements, have been observed. Variable speed compressors will tend to be smaller displacement, with pulldown requirements met by overspeed operation.

Present commercially available low capacity compressors (<600 Btu/hr nominal capacity) have very poor efficiencies, low enough in some cases to completely negate the gains obtained from the design options described above. To realize the efficiency benefits of reduced loads and dual evaporator systems will require improved efficiency, lower capacity compressors.

Regardless of the R/F cabinet and refrigeration cycle design approach taken, increases in the efficiency level that is available in refrigerant compressors will result in proportional increases in the efficiency of the refrigerator using the compressor.

A major issue for compressor design is the change in refrigerant from CFC-12 to a low ozone depletion, low global warming potential refrigerant. While CFC-12 has been shown to be a significant part of the cause of both stratospheric ozone depletion and global warming, it is an excellent working fluid for domestic refrigerator/freezers. It has a favorable pressure-temperature relationship, good thermodynamic efficiency, stability, total miscibility with low cost mineral oil, and moderate temperature rise with compression and is non-flammable, non-toxic, and low cost. Alternate refrigerants that do not contain chlorine or have currently acceptable ozone depletion potentials do not possess identical attributes of CFC-12. Thus, compressor modifications or new designs will be required to adapt to the characteristics of a selected alternative refrigerant. Table 2-1 lists some of the potential alternative refrigerants and their status, including potential substitutes for CFC-11, CFC-114, and CFC-502, as well as for CFC-12.

The major working fluid options include the near drop in replacements for CFC-12 (i.e., those refrigerants having vapor pressure-temperature curves close to that of CFC-12), lower vapor pressure refrigerants such as HCFC-124, and non-azeotropic refrigeration mixtures (NARMs). Lower vapor pressure refrigerants might be utilized in low capacity systems (design options described above), if shown to result in higher efficiency of low capacity compressors, by virtue of the larger displacement that would be needed. The Lorenz cycle would utilize a NARM.

**Table 2-1: Alternative Refrigerants**

| Substitute Refrigerant | Displaced Refrigerant | Probable Availability | Description, Status, Comment |
|---|---|---|---|
| HCFC-22 | CFC-12<br>CFC-502 | Current | Commercially available, widely used refrigerant. Contains chlorine, will be phased out under Montreal Protocol Copenhagen Amendments |
| HFC-134a | CFC-12 | Current | Commercially available, rapidly expanding production |
| Ternary | CFC-12 | (w/HCFC-124) 1993 | Available in limited amounts |
| HFC-152a | CFC-12 | Current | Commercially produced and sold in fairly small quantities, used primarily as a component in CFC-500 (26%) and as a component in aerosol propellant blends |
| HFC-123 | CFC-11 | 1990-1991 | Toxicity tests have shown sufficient toxicity to set AEL at 10 ppm; commercially available |
| HFC-124 | CFC-114 | 1993-95 | Co-product of HCFC-123 production. Long term toxicity testing started |
| HFC-125 | CFC-502 | Available in limited amounts | Near-term availability in blends to replace CFC-502 |
| HCFC-141b | CFC-11 | Current | Commercial production began in July 1988. Toxicity testing underway. Possible use as a foam blowing agent |
| HCFC-142b | CFC-12, 114 | Current | Used in R22/R142b blends |
| $NH_3$ | CFC-11<br>CFC-12<br>CFC-502 | Current | Commercially available. Widely used in industrial refrigeration sector. Toxic with low flammability |

Source: Arthur D. Little, 1993

The major issues that need to be considered in adapting the compressor design to an alternate refrigerant include the displacement required to obtain the intended capacity, lubricant selection, and material compatibility, especially the motor winding insulation.

In summary, higher efficiency compressors are needed, especially in smaller capacities. Motor technology is an important consideration, because increasing the efficiency of the compressor motor is a straightforward way to improve compressor efficiency. For variable speed compressors, the variable speed motor and electronic drive represent the major technology component and the major cost driver.

## 2.1 Motor Technology Options

Motor efficiency impacts the overall energy consumption in a refrigerator/freezer in two ways: 1) the compressor energy use is directly related to the motor efficiency for any given compressor pump work; and 2) motor inefficiencies may result in additional compressor pump work requirements due to heating of the working fluid within the compressor shell. Because of the combined effect of these two factors, a 10% increase in motor efficiency could result in an overall compressor energy reduction of 13 to 16%.

The use of variable (either two-speed or continuously variable) speed compressor operation, to reduce cyclic losses and improve heat exchanger utilization, has proven to result in significant improvements (of approximately 25% to 30%) in seasonal efficiency in air conditioning (Cann, 1989; Sulfstede, 1989) and commercial refrigeration applications. These improvements accrue from reduced heat exchanger loadings, which will result in thermodynamic performance advantages. In addition, cycling losses are reduced by longer, or continuous, compressor operation. Potential disadvantages are additional losses associated with electronics and increased fan energies

Improvements might be achieved in domestic refrigerators, as well. Applications to these smaller capacity ranges have been limited due to the costs of the electronics and the current lack of a market demand. A major requirement for energy savings is the reduction of fan and electronics energies during the lengthened cycle time. Again, advanced motor technology will be required to realize the potential efficiency improvements.

In view of the importance of motor technology to the potential efficiency improvements of various design alternatives, this review of the motor technology applicable to small hermetic refrigeration compressors was undertaken as part of a larger study to evaluate the options for maximizing the efficiency of domestic refrigerators. The motor characteristics documented in the report are being used in the overall study as part of the input database for modeling and evaluating design options.

This report covers the technology status of electric motors to drive the small hermetic compressors used in the refrigeration system of domestic refrigerators. Two general areas are addressed:

- The potential for and cost of improvements in the efficiency of the motors currently used in small hermetic refrigeration compressors, with particular emphasis on the motors used in smaller (<800 Btu/hr nominal capacity) compressors.

- The status of variable speed (both two discrete speeds and continuously variable speed) motors in terms of availability, efficiency, and cost.

This report is intended to serve three functions: 1) description of the state-of-the-art of current motors and the potential for future improvements; 2) summary of performance and cost data as input to evaluations of refrigerator/freezer system design options; and 3) present preliminary results indicating the level of R/F energy consumption reductions that can be obtained through the use of variable speed compressor operation.

## 3.0 *Single Speed Induction Motors - Current Practice in Refrigerator/Freezer Compressors*

The compressors used in all domestically produced and sold domestic refrigerators and freezers in the U.S. are powered by 2 pole AC squirrel cage induction motors that operate on normal household line power, i.e. 115 VAC, 60 HZ, 1 phase. The motors run at a single speed, near 3500 RPM. In addition to running the compressor at the normal range of loads, the motor must provide adequate starting torque, because small, single cylinder compressors are difficult to start.

As shown in Figure 3-1, the basic arrangement of this type of motor consists of a rotor and stator, each built up of a stack of electromagnetic grade steel laminations, as shown in the cut-away rotor in Figure 3-1. The "squirrel cage" rotor has a series of lengthwise aluminum bars cast into the rotor laminations. These bars are connected by rings at each end of the stack. The stator laminations have a series of slots for the windings which are aluminum or copper wire. Two sets of windings are provided, one being 90° out of phase with the other. The main, or run, winding operates directly from line current, and is always energized when the motor is running. The major design categories of this type of motor involve the manner in which the secondary winding is utilized for starting the motor and then running at normal speed. The basic categories of induction motors are:

- RSIR or Resistance Start/Induction Run;
- CSIR or Capacitor Start/Induction Run; and
- PSC or Permanent Split Capacitor.

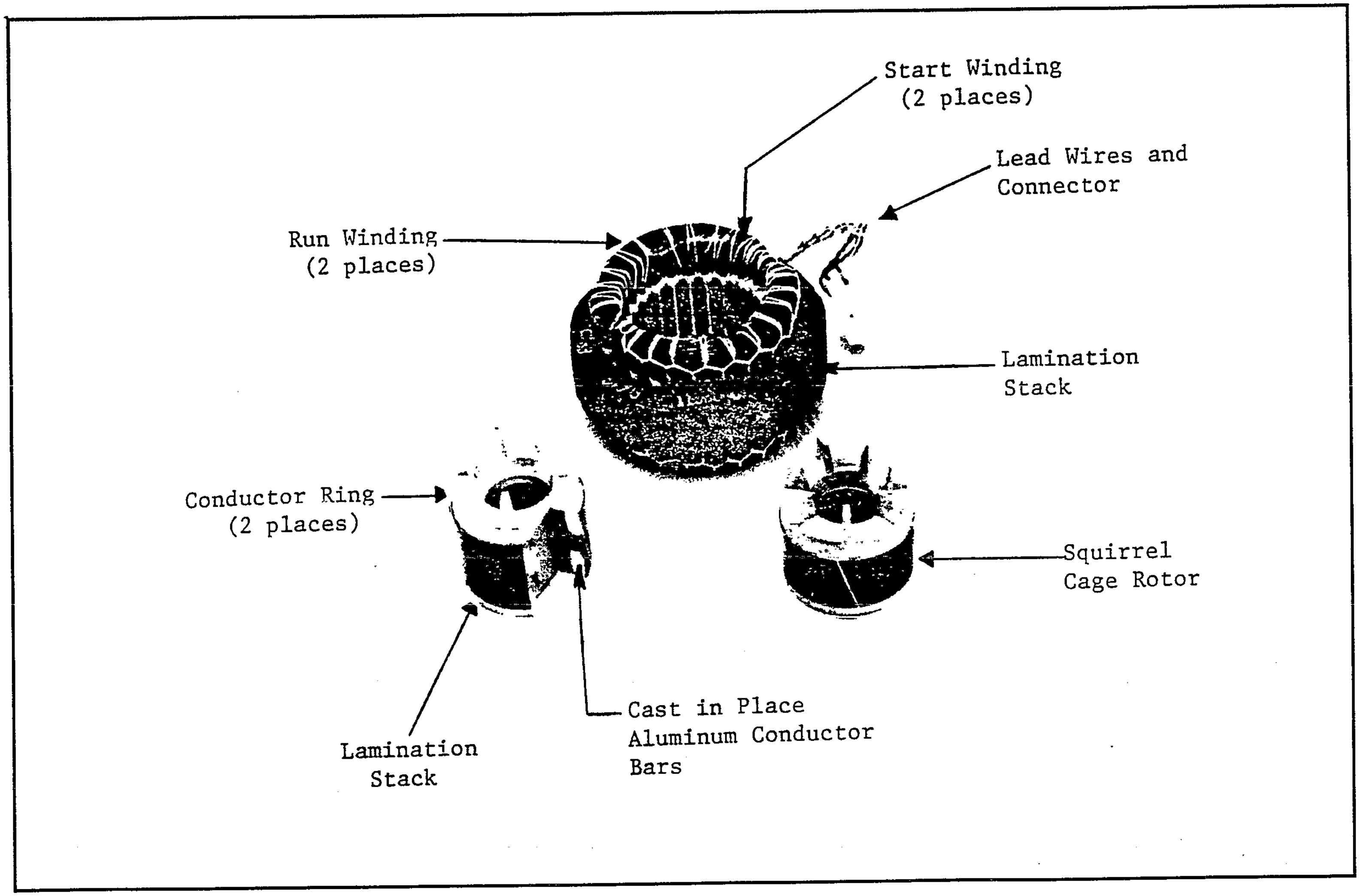
RSIR and CSIR motor use the secondary winding for starting only, the capacitor start version providing higher starting torque. As shown in Figure 3-1 (a photograph of an RSIR rotor and stator), the secondary winding uses much smaller diameter wire, which can be energized for only a limited period of time without overheating. The RSIR motor is very low cost, but is inherently limited to 8 - 10 percent less efficiency than PSC motors. In PSC motors, the secondary winding also operates when the motor is running. A capacitor in series with this winding shifts the phase of the input voltage approximately 90°, so that both windings together create a rotating magnetic field. The net effect is improved utilization of both the windings and the iron in the motor, increasing the efficiency, but at the added cost associated with the capacitor.

Motor efficiencies may be improved by the following:

- Using additional material (increasing stack height and using larger diameter wire);
- Using low loss steel in the laminations; and
- Using thinner laminations

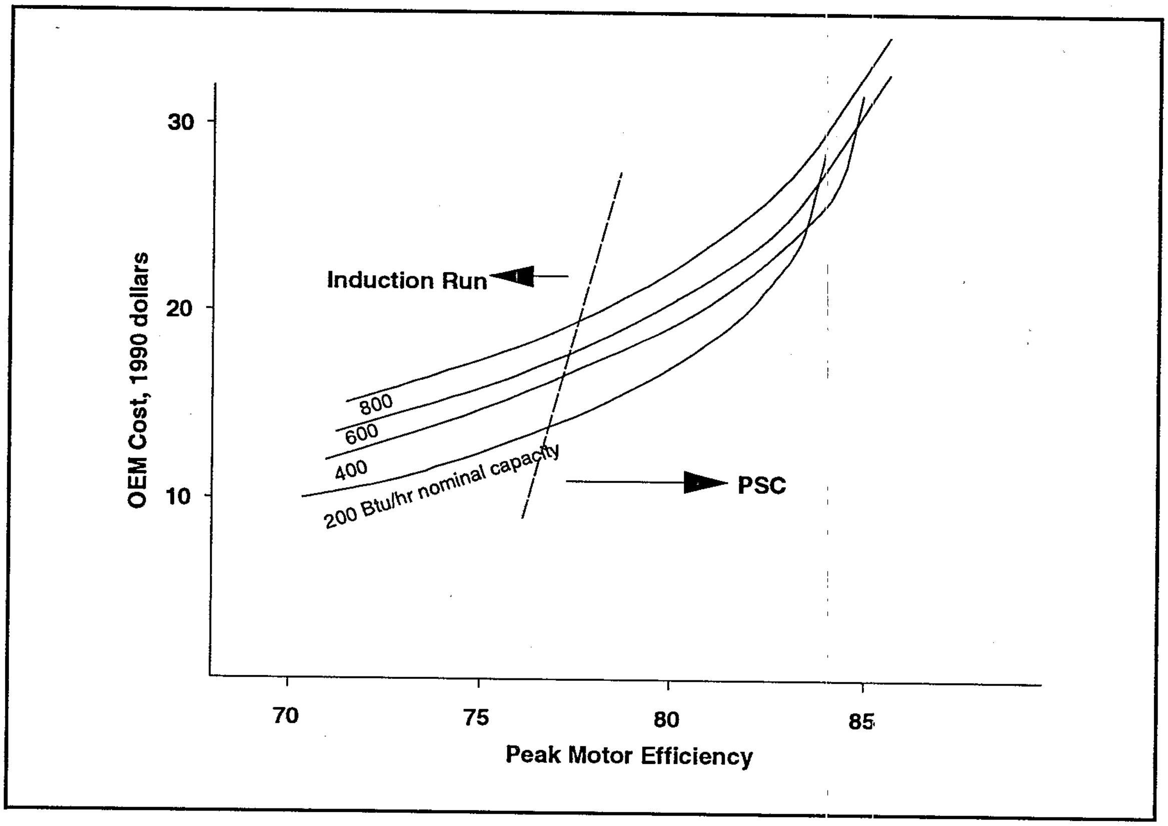
Figure 3-2 plots the estimated cost per motor (basis: the OEM price paid to the motor supplier by the compressor manufacturer for production quantities of the motors) of single speed induction motors vs. efficiency for motors sized for compressors having nominal capacities between 200 and 800 Btu/hr. Note that for the smaller motors, the maximum physically attainable efficiency is lower than for the larger motors, and as a

**Figure 3-1: Typical Squirrel Cage Induction Motor Used in Domestic Refrigerator Compressors (RSIR example)**



result, the cost-efficiency curves cross. Table 3-1 compares present practice in this capacity range with estimated maximum efficiencies inherent in this motor type. From Figure 3-2 and Table 3-1, it is apparent that:

**Figure 3-2: OEM Cost of Single Speed Induction Motors for Hermetic Refrigeration Compressors, Versus Motor Efficiency and Compressor Capacity**




OEM Cost: Price each paid by compressor manufacturer to motor manufacturer for mass production quantities. Includes cost of required relay, capacitor, etc.
Efficiency: Not accounting for any mechanical losses
Source: Table 3-1 and informal discussions on OEM cost levels with OEM suppliers of motors and manufacturers of refrigeration compressors

- High motor efficiency (peak efficiency near 85%) is technically feasible in any compressor capacity of interest, once all of the aforementioned measures to improve efficiency have been applied.

- The cost of attaining the highest efficiency is significant, qualitatively. For the smaller compressor capacities, the highest efficiency motors could cost up to 2 to 3 times more than the cost of the motors typically used currently.

**Table 3-1: Refrigerator Compressor Induction Motor Efficiency**

| | | Today's Motor | | Possible | |
|---|---|---|---|---|---|
| Compressor Rating | Motor HP | Type | Efficiency | Type | Efficiency |
| 200 Btu | 1/16 | RSIR* | 70-73% | PSC** | 84% |
| 400 Btu | 1/8 | RSIR | 73-76% | PSC | 86% |
| 600 Btu | 1/6 | RSIR/PSC | 78-82% | PSC | 86% |
| 800 Btu | 1/4 | PSC | 80-84% | PSC | 86% |

*RSIR - "Resistance Start/Induction Run" Type Motor - requires relay.
**PSC - "Permanent-Split Capacitor" Motor with PTCR start-assist device - requires capacitor.
Source: Data provided by GE Motors, 1/12/90

Only a few manufacturers produce compressor motors for R/F applications. Americold, Matsushita, and Embraco make them for their own compressors; Americold supplies compressors primarily to White Consolidated Industries. GE makes these motors for sale to all compressor manufacturers. Tecumseh manufactures most of the motors for their small compressors. A.O. Smith and Copeland make motors in the 1/2 and integral horsepower sizes; Copeland provides them only for their compressors. Industrias Copreci of Spain makes compressor motors, but they have not entered the U.S. market.

## 4.0 Two Speed Motors

Two speed motors provide a method for potentially improving system performance because frequent on-off cycles can be largely replaced with long periods of half speed operation, with reduced evaporator and condenser coil loading. There are two basic arrangements of two speed motors, consequent pole and arrangements with separate sets of two pole and four pole windings. The former arrangement is simpler, more compact, and lower cost, but inherently lower in half speed efficiency in a fractional horsepower motor.

Based on the limited information that is available relative to two speed motors for this application, the performance and cost characteristics of a two speed motor for an 800 Btu/hr compressor, optimized for low speed efficiency, are (reference 5):

- 80% full speed efficiency
- 70% half speed efficiency
- Cost approximately that of a maximum efficiency single speed motor (Figure 3-2, Table 3-1)

These efficiency numbers represent the estimated highest level of efficiency that might be attained for this type of motor, in the output needed to operate an 800 Btu/hr compressor. It should be emphasized that no 2 speed motors are actually in production at this time for this application. Cost and efficiency estimates are the result of presales preliminary design studies of a major supplier, and are subject to considerably more uncertainty than the cost-efficiency curves in Figure 3-2 for single speed motors.

Table 4-1 shows some two speed motor manufacturers and the availability of two speed motors. Two speed motors are not available from many U.S. motor manufacturers in this size range. A.O. Smith and Copeland have made 1/2 and 1/3 horsepower compressor motors but these are not in production. Baldor has made a 1/3 horsepower compressor hermetic motor but it is three phase. Other manufacturers, including Emerson, G.E., and potentially Americold are working on the development of two speed motors at this time. The technology exists to make two speed motors, but there is not a large enough market for them now. Two speed motors are most frequently used for fans and pumps in integral horsepower sizes. Some residential central air conditioning applications in the 1 1/2 to 5 horsepower range and larger use two speed compressors, including Bristol (produces the 2 speed compressor), Copeland (produces the 2 speed compressor), Lennox, Goodman (Janitrol), and Carrier.

**Table 4-1: Potential Two Speed Motor Manufacturers**

| Manufacturer | Smallest Size (hp) | Status |
|---|---|---|
| A. O. Smith | 1/2 | not in production |
| Copeland | 1/3 | not in production |
| Baldor | 1/3 | 3 phase only |
| GE | | some development |
| Americold | | possible development |
| Emerson | | some development |

Source: Americold, 1990; Baldor, 1990; Copeland, 1990; Emerson Electric, 1990; GE Motors, 1990; A.O. Smith, 1990.

## 5.0 Variable Speed Drives

Variable speed drives allow motors to operate over a continuously variable speed range, with the maximum speed not limited to the 3500 - 3600 RPM maximum speed of a 60 Hz induction motor. In domestic appliance applications, the variable speed drive is an electronic device that converts input line electric power (115 VAC, 60 Hz, single phase) to a multiple phase, adjustable output voltage and frequency, driving the motor at variable speed. Potential benefits of variable speed drive of the compressor include:

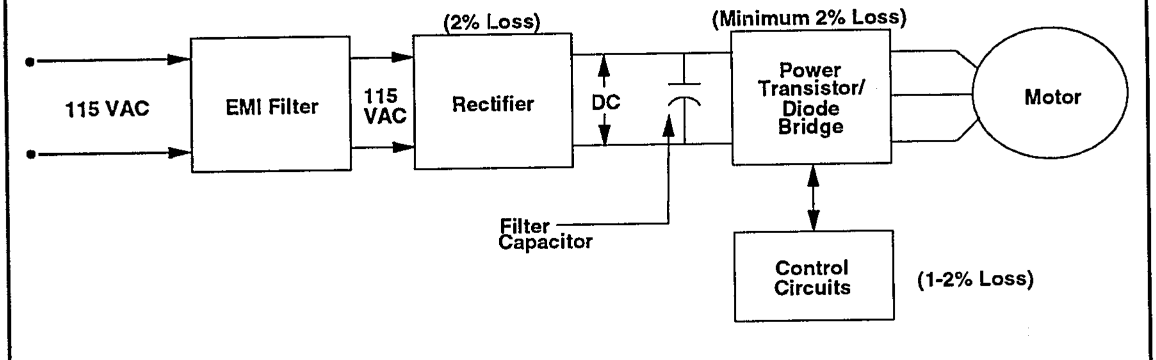
- Follow refrigerator loads closely
- Allow for quick pull down
- Reduce evaporator loading
- Potential for better matching of individual evaporator loads in a cycled two evaporator system
- Maximum speed can be greater than 3600 RPM, allowing reduced compressor displacement, size, and cost
- Reduce cycling losses
- Reduce frosting

Variable speed drives are either commercially produced, or under development, to operate three general categories of motors that are potentially applicable to domestic refrigerator/freezers:

- Three phase induction motors
- Electronically commutated permanent magnet rotor DC motors (ECPM)
- Switched reluctance motors

The basic electronic hardware configurations of the variable speed drives used to operate each of these motor types are very similar to each other. Figure 5-1 is a simplified block diagram of a "generic" variable speed drive, highlighting the similarities. After passing through an EMI filter (to minimize the transmission of electronic noise back onto the AC line), the input AC is rectified and filtered to DC. Output transistors switch the DC to the individual motor windings, to suit the characteristics of the motor being driven. Figure 5-2 is a photograph of a one quarter horsepower variable speed drive containing these major subsystems, that has been developed for a specific appliance application. In general, to drive any of the three motor types over a wide speed range requires that the motor input voltage be varied, and, for induction motors, that the DC supply be switched to synthesize an approximately sinusoidal A/C output. Pulse width modulation (PWM) is the technique most commonly used to effect this voltage variation. Figure 5-3 illustrates the operation of PWM, to vary the input voltage to a DC motor. An output transistor is switched on and off at a much higher frequency than the motor rotation frequency. The output voltage is varied from 0 to the DC supply voltage by varying the length of the on time of the output transistor from 0 to the full period of the square wave. The inductance of the motor winding stores energy in excess of the average DC voltage during the pulse on time, and releases the energy during the pulse off time to maintain current flow, smoothing the electric current to a nearly constant level (or, in an induction motor, nearly sinusoidal wave form). During the off period of the pulse, current passes through a diode "bypassing" the power transistor.

**Figure 5-1: "Generic" Variable Speed Drive Block Diagram**



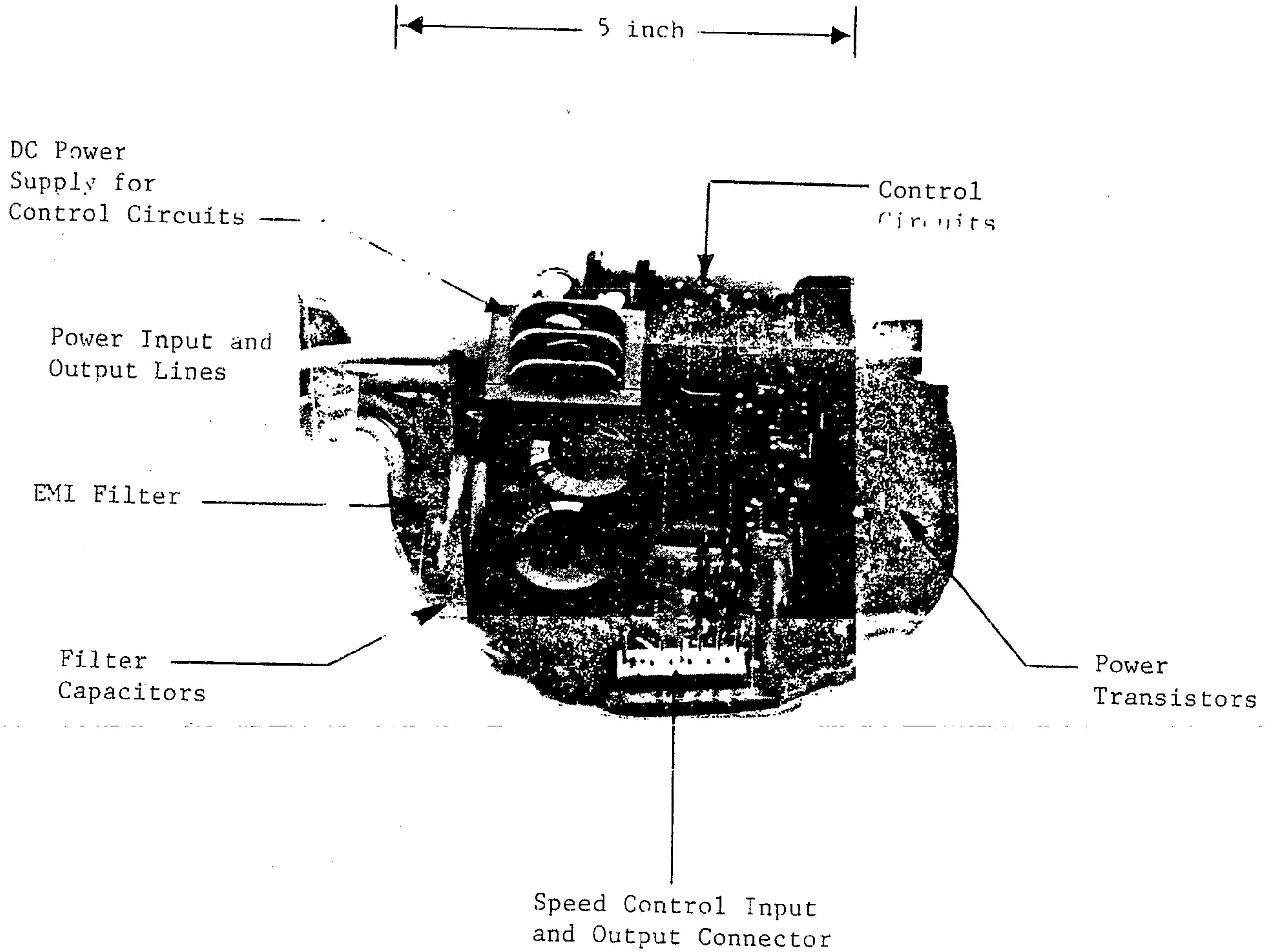

Source: GE Motors, 1990; Toshiba a,b; Lloyd, 1982

There are a variety of other techniques for varying motor speed electrically or electronically, that are in use or under development. Those in use are generally used in specialized industrial applications, usually at power levels in excess of 25 horsepower. The three variable speed drive/motor combinations covered in this section represent those technologies that have been developed, or are undergoing development for mass market appliance applications and have the best potential for low cost production.

In addition to controlling the output transistors as required to control the speed of the motor, the control section often performs other functions such as: fault detection, protection, and reporting; status monitoring; driving panel displays; controlling additional operation functions, such as reversing the rotation direction and dynamic braking; overload protection; torque limiting; and others. Many general purpose inverters include a large selection of these features, adding considerably to the cost. In a cost driven appliance application, only those functions that are actually useful would be included.

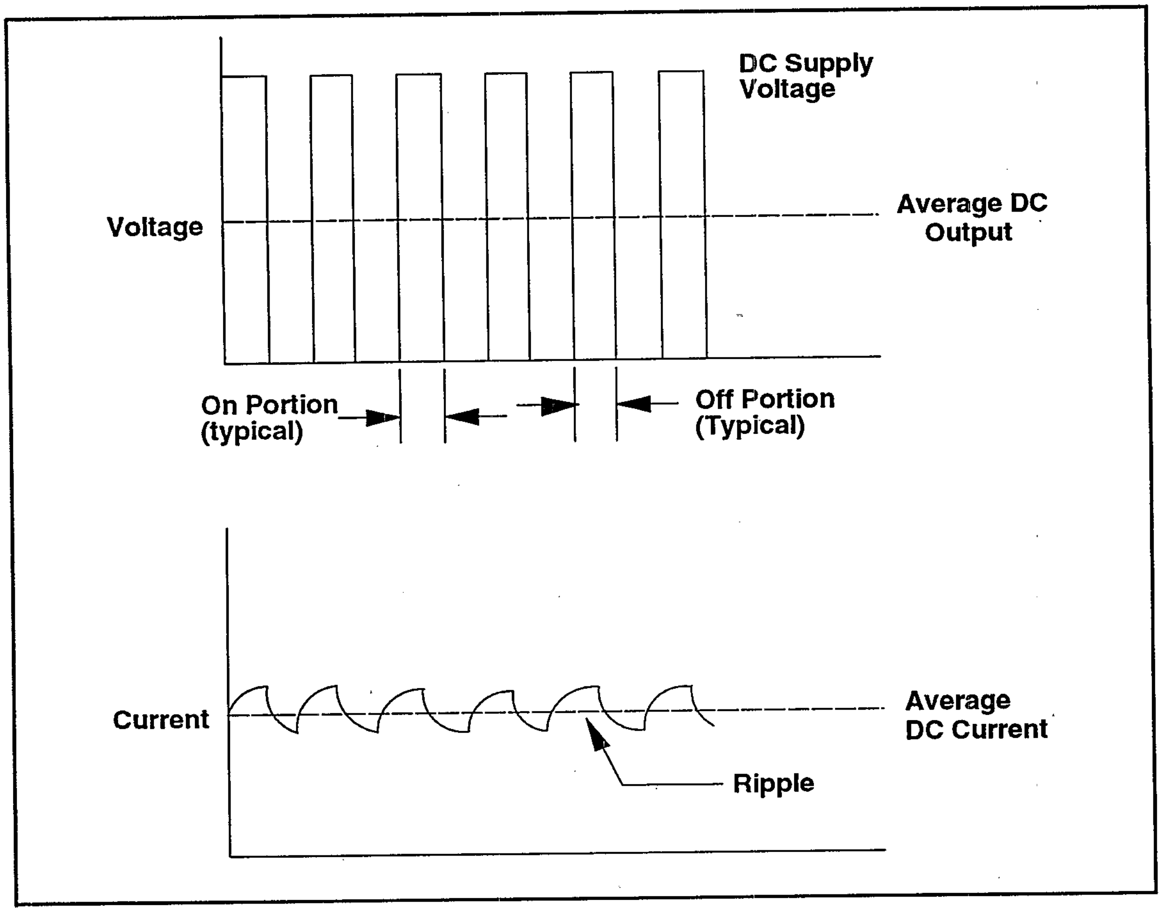
As the number of variable speed drives in service increases, regulations are likely to be imposed requiring low frequency harmonic filtering (in addition to higher frequency EMI filtering) on the input line. This type of regulation is already in place in Europe for electronic motor drives drawing more than 200 watts from the AC line. This type of filtering adds components and cost to the variable speed drive, with little effect on the efficiency.

**Figure 5-2: Variable Speed Electronic Drive for a One-Quarter Horsepower Electronically Commutated DC Motor**




Source: Arthur D. Little photograph of ECM drive manufactured by GE Motors

Figure 5-3: PWM Operation for Varying Output Voltage to a DC Motor




## 5.1 Efficiency

The overall efficiency of a variable speed motor and drive (shaft power output ÷ AC line electric power input) is the product of the electronic drive efficiency and the motor efficiency. Electronic drive efficiency for the three types of drive is nearly identical, because the configuration of the power electronics (EMI filter - rectifier - filter - output transistor/diode bridge) is essentially identical for each of the three drives. The efficiency decreases with decreasing output voltage (and motor speed) and, to a lesser extent, with decreased load (torque).

For small motors, the inherent efficiency of the three motor types are ofset from each other by small increments:

- ECPM's have the highest efficiency, approaching 95% (motor only), because the field is supplied by the permanent magnet rotor, with no electric resistance losses. ECM's incur only minor ripple loss from PWM operation at intermediate input voltages and speeds.

- Three phase induction motors are approximately 5 percentage points lower in efficiency than ECPM's. The PWM waveform causes an additional 3-5% efficiency degradation, at a reasonably high PWM frequency (10 KHz) and 5 - 10% degradation at low PWM frequency (1 - 2 KHz), due to the content of higher harmonics of the pulsed waveform.

- Switched reluctance motor efficiencies are intermediate to the other two types, but require very high quality iron in the laminations, and very precise timing of energizing and deenergizing the stator poles, to attain the intermediate efficiency level.

Figure 5-4 plots overall motor/drive efficiency vs. motor speed for each of the three basic motor types (applicable to between 1/10 and 1/3 horsepower output).

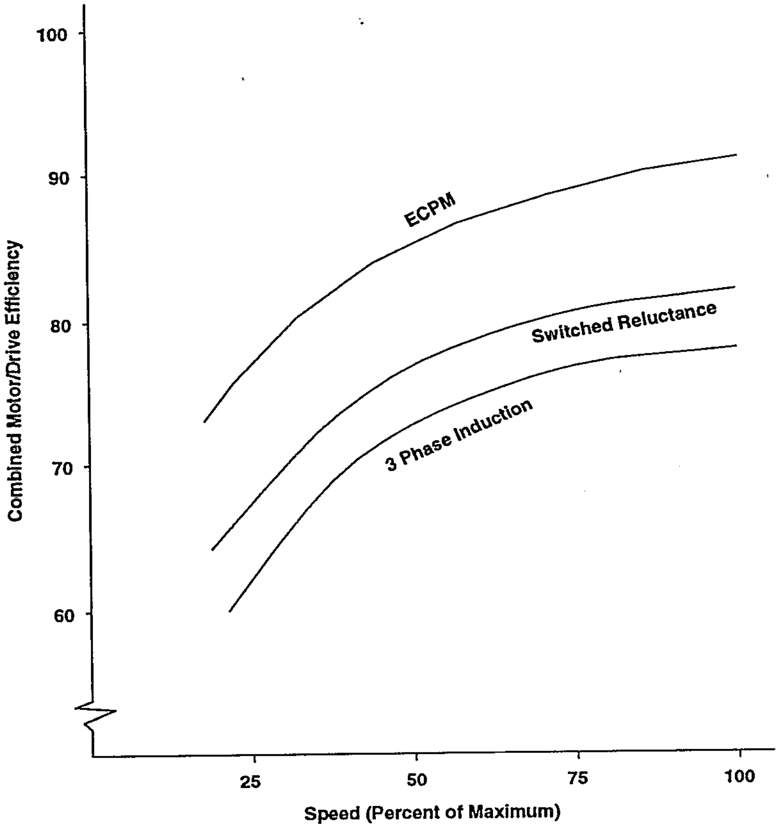
## 5.2 Variable Speed Motor/Drive Costs

This subsection addresses prospective mass production costs of variable speed drives for refrigerator compressor application. Sections 5.4.1 through 5.4.3 present current costs for commercially available drives.

Estimates of eventual mass production costs of variable speed drives are subject to considerable uncertainty, because there is no U.S. mass production (on the appliance industry scale) and corresponding OEM sales upon which to base cost estimates. In general OEM prices and manufacturing costs are commercially sensitive information which manufacturers are reluctant to divulge to the public at large. General Electric is marketing variable speed, electronically commutated motors, targeting mass market applications - appliances, air conditioning, and automotive - and currently have total motor/drive system sales for all applications approaching 50,000 units annually. Applications range from 5 horsepower heat pump compressor drive motors to one half horsepower indoor air blower motors for central air conditioning systems. The latter (packaged one half horsepower, 1200 RPM motor and drive) are being sold to OEM customers for approximately $125 each, with specific prices depending on volume and other commercial arrangements (GE Motors, 1990). In Japan, PWM inverters are mass produced for small "mini-split" heat pump applications, reportedly at a manufacturing cost of the inverter of $25/horsepower (at average rated motor power output of about 1 1/2 horsepower) (Greenberg, 1988 p. 7). Others place the large volume purchase direct material cost of the complete inverter in the Japanese mini-split heat pumps (the major blocks shown in Figure 5-1 plus low frequency harmonic filtering on the input) at approximately $70 per horsepower (GE Motors, 1990). With assembly costs, overhead, and profit margin added in, full OEM pricing would be on the order of $100 to $125 per horsepower.

It can be expected that the ultimate mass production OEM cost of a one quarter horsepower motor and stator plus a drive on a printed circuit board (see Figure 5-2) will be well under the $100 level. The cost of the motor will be similar to the cost of premium efficiency single phase AC induction motors (Figure 3-2), on the order of $25,

**Figure 5-4: Comparison of Variable Speed Drive/Motor Efficiencies (Fractional Horsepower)**




Source: Arthur D. Little estimates based on data from references 5, 13-15.

varying with output in the same fashion as induction motors. The OEM cost of the variable speed drive (either PWM inverter or ECPM drive with PWM speed control) after several years of mass production can be expected to fall to between $25 and $40, and be relatively insensitive to the power output level, as the control portion of the circuit cost becomes a significant portion of the total. To reach this cost level requires a very high level of integration of control circuitry.

The cost of the controller could be offset, to some extent, by operating the motor and compressor at higher speeds, up to approximately 6000 - 7000 RPM, at nominal capacity. Operating speeds of this magnitude are common practice for the variable speed rotary compressors used in mini-split, room sized air conditioning systems, and should be compatible with the smaller compressors used for R/Fs. This range of operating speed has also been demonstrated in R/F capacity reciprocating compressors, on a laboratory project basis (GE, 1990). In either case, the normal range of compressor design optimization and durability issues would need to be addressed prior to commercial production based on these higher speeds, but the higher speeds are clearly feasible.

The resulting reduction in compressor displacement and motor size would allow some reduction of the cost of these components, on the order of $5 to $10 at the OEM cost level. The variable speed drive and motor replace the standard induction motor, whose OEM cost is on the order of $15. The total of these offsetting cost reductions is on the order of $20 - $25; the net increase in OEM component cost to the R/F manufacturer associated with the VSD/motors, in mass production, can be expected to be on the order of $25 - $30.

Total applied costs will include, in addition to motor and drive cost, the cost of the refrigerator temperature controller, whose function is to determine the required compressor speed and generate a speed control signal to the motor drive based on cabinet interior temperatures and a control algorithm. These components replace the mechanical thermostats used in current refrigerators. In production, the costs could be expected to be comparable, with no net effect on the manufacturing cost or retail price of an R/F.

### 5.3 Variable Speed Drives - Life, Reliability

Domestic refrigerators typically operate for periods on the order of 15 years, and do so at a very high reliability level. Electronic variable speed drives have been available for about two decades; drives technologically similar to todays state of the art drives have been produced for well under 10 years. The latter time period is insufficient to establish life and reliability relative to the 15 year expected lifetime of the refrigerator. In general, however, electronic variable speed drives have established a good reliability track record, consistent with solid state electronics in general. Key to achieving longevity is provision of adequate cooling for the power electronics components and control of environmental factors such as moisture condensation.

Simply by virtue of adding another component having a finite possibility of failure, the addition of a variable speed drive might be expected to reduce the overall reliability of the appliance. However, a number of factors related to the variable speed drive are favorable to overall reliability:

- Electromechanical contactors, such as the relay used to switch the start windings in a conventional induction motor are replaced with the more reliable solid state electronics of the variable speed drive.
- Control circuits will tend to be exclusively highly reliable solid state devices, replacing the more failure prone electromechanical defrost timer, and thermostat.
- The already high level of compressor mechanical reliability will be improved by reduced frequency of stop-start cycles.

Overall, given the high reliability of solid state electronics, it is reasonable to expect that variable speed drives could be used in the domestic refrigerator without significantly impacting the overall reliability of the appliance.

## 5.4 Description of Specific Variable Speed Motor/Drive Types

The following subsections present brief descriptions of the operating principle of each of these motor types with a variable speed drive, with a brief summary of the current commercial status of each of the three VSD-motor technologies.

### *5.4.1 Electronically Commutated Permanent Magnet Rotor DC Motors*

Electronically commutated permanent magnet rotor DC motors, also commonly referred to as "brushless DC" motors, have a permanent magnet rotor and (usually) three sets of stator windings. As the rotor rotates, the stator windings are commutated, i.e. switched in phase with the permanent magnet poles on the rotor. To control commutation timing, rotor position is sensed and fed back to the ECPM controller and used as the basis for timing the switching of the current to the motor windings by the power transistors in the controller. In many brushless DC motor product offerings, rotor position is sensed by Hall effect sensors in the motor. An additional set of lead wires is required to connect the sensors to the controller. An alternate technique, developed and used by GE, senses the back EMF in the off winding, and commutates on an initial rise of the EMF. The advantages of this technique are the obvious cost savings of eliminated Hall effect sensors and lead wires and, for hermetic compressors, the reduction of the number of wires (to three) that must penetrate the hermetic shell of the compressor, reducing cost and improving reliability.

The basic operational characteristic is identical to a conventional brush-type permanent magnet DC motor (speed is proportional to DC supply voltage, torque is proportional to current). To provide for variable speed operation, the ECPM controller must vary the DC supply voltage to the motor, as well as providing for correctly timed commutation. Pulse width modulation is a cost effective and efficient means of varying the DC voltage supplied to the motor (Figure 5-3), because the high speed PWM switching is done at the same output transistors used for commutation. The effect of the high speed PWM switching on the motor is a low level of ripple in the DC voltage and current to the motor, which results in a modest increase in $I^2R$ losses (decreasing the motor efficiency by on the order of one percent) in the stator windings.

The high efficiency of electronically commutated DC motors is attributable to two basic attributes of the motor:

- The permanent magnet rotor supplies the field, without requiring any input power, as required with induction motors and wound field type DC motors.

- The placement of the windings on the stator allows room for more winding wire cross section, allowing lower $I^2R$ loss than in a typical brush type DC motor.

Permanent magnet materials that are used for ECPM rotors are:

- Ferrite;
- Rare earth - cobalt (samarium-cobalt); and
- Neodymium - Iron - Boron (e.g. "Magnequench")

Ferrite magnets are relatively low in magnetic field strength and cost. The latter two materials have much stronger fields, resulting in more compact motors and more power output from a given size stator. The cost, however, is considerably higher, so that currently the least costly motor uses a ferrite rotor. There is a general expectation that the Neodymium - Iron - Boron material will decrease in cost to the point where it is cost effective. Table 5-1 lists suppliers of electronically commutated DC motors.

**Table 5-1: Manufacturers of ECPM Controllers**

| Manufacturer | Available Size (hp) | Present Cost (quantity 1) | Comments |
|---|---|---|---|
| General Electric | 1/5 - 8 1/2 | 250 - 300 | in production |
| Emerson | 1 | | starting production |
| Inland Motors | 1/4 | 1,700 | custom |
| Magnetek | custom | | custom |
| PMI | custom | | custom |
| Minarik | custom | | custom |
| EG & G | custom | | custom |
| Fasco | custom | | custom |

Source: Telephone conversations and/or product literature of the manufacturers listed.

### *5.4.2 Pulse Width Modulation Inverter/3 Phase Induction Motor*

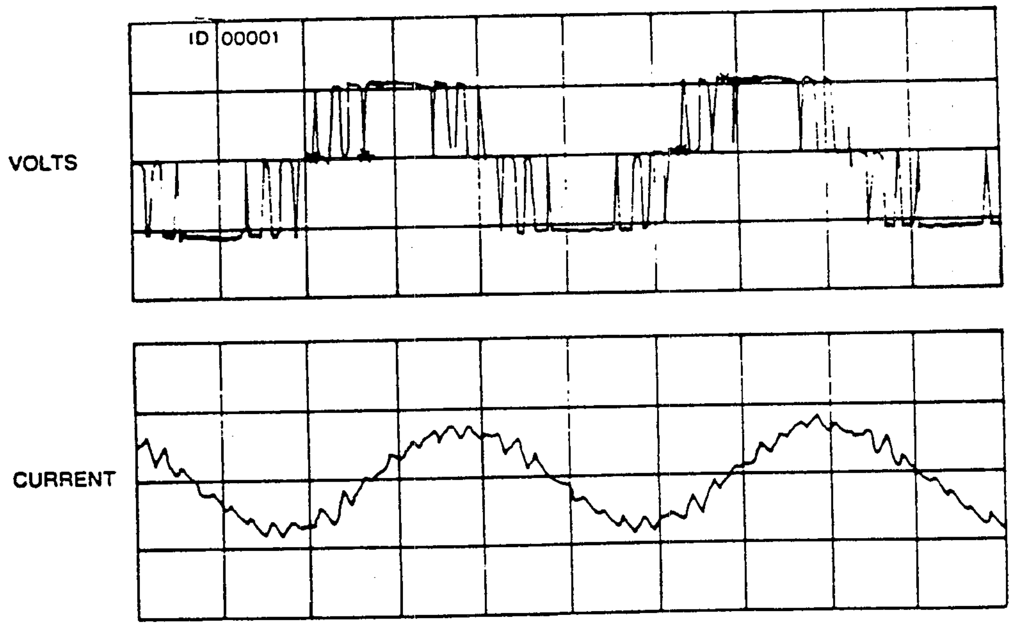
PWM inverters convert fixed frequency and voltage input electric power (e.g. 115 volt, 60 Hz, single phase residential electric power) into 3 phase variable frequency and voltage output to an essentially conventional 3 phase induction motor. The PWM inverter is a specific case of the "generic" variable speed drive of Figure 5-1, where the PWM output of the output power transistors is switched to approximate the sinusoidal voltage required to drive the induction motor efficiently. Figure 5-5 shows the voltage and current waveforms that are typical of a PWM (with a relatively low PWM frequency) inverter driving an induction motor.

In comparison with electronically commutated motors, PWM inverter driven, fractional horsepower, induction motors are inherently limited to efficiencies roughly 10-15 percentage points lower. The major reasons for this are:

- The induction motor maximum efficiency is a few percentage points lower than the ECPM, for the reasons discussed in 5.4.1.

- The PWM sinewave approximation (Figure 5-5) results in some degradation of the motor frequency, because of ripple and harmonics associated with the PWM square waves. In addition, the PWM frequency is generally on a fixed carrier that is not precisely synchronized with the timing of the output waveform. This results in some asymmetry to the waveform, adding additional harmonic content to the waveform. The net result is lower motor efficiency, by 3 to 5% for high PWM frequency, and by 5 to 10% for low PWM frequency.

Figure 5-5: Voltage and Current Output of a PWM Inverter (approximate PWM frequency: 1.1 kHz)




Source: Toshiba product literature

Partially offsetting the efficiency difference is a small advantage in induction motor cost in comparison with permanent magnet rotor motor cost, attributable to the difference in materials cost between a squirrel cage rotor and a permanent magnet rotor.

PWM inverters are widely used in the U.S. for 3 phase motor speed control in industrial applications, primarily in integral horsepower and larger output. Table 5-2 is a partial listing of sources of PWM inverters and current selling prices, which reflect low volume production, small lot sales requiring significant application engineering assistance, and the inclusion of various control, fault detection, and motor protection features beyond those required to simply run the motor.

**Table 5-2: Manufacturers of PWM Inverters**

| Manufacturer | Size (hp) | Model | Present Cost (quantity 1) | Comments |
|---|---|---|---|---|
| Toshiba | 1/4 | E Series | 750 | |
| Emerson | 1/2 | Prism | 600 | |
| Mitsubishi | 1/2 | Freqrol-F2, K | | |
| Hitachi | 3/4 | VWE | 550 | |
| Westinghouse | 1 | AccuFlow JR | 585 | |
| MagneTek | 3/4 | FHP 402 | 610 | |
| Lenze | 1/4 | | | |
| Vee-Arc | 3 | PWM 7030 | 1575 | AC applications |
| Ranco | 3 | | 500 | AC applications, starting production |

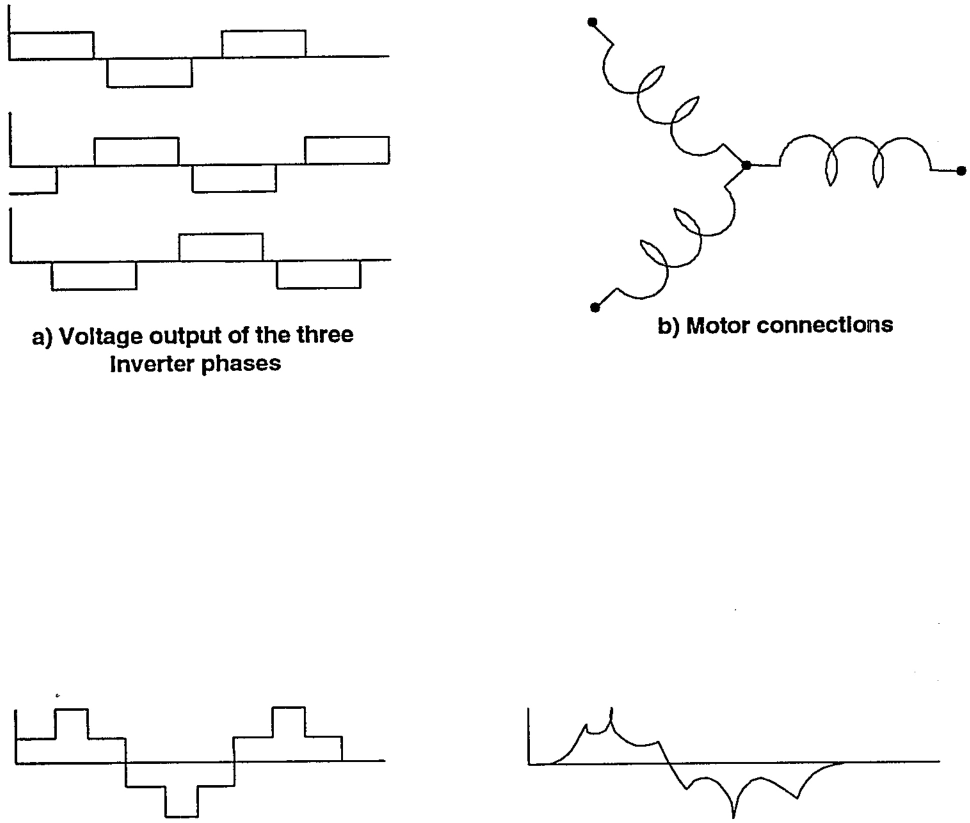
Source: Telephone conversations and/or product literature of the manufacturers listed.

### 5.4.3 Six Step Inverter - 3 Phase Induction Motor Drives

Single phase voltage is first rectified and filtered, with SCR's in the rectifier to provide a controlled, variable DC voltage. This voltage is then switched six times per cycle (twice per phase times three phases) in order to emulate stepwise sine waves. The line current will rise in an exponential manner and resemble a scalloped sound wave, since motors are inductive devices. Typical voltage and current signals from a six step inverter are shown in Figure 5-6.

Six step inverters are an essentially obsolete alternative to PWM inverters for driving small, 3 phase induction motors at variable speeds. 10 to 15 years ago, when PWM frequencies were limited to levels well under 1 KHz, the PWM approximation of a sine wave was poor, and the higher harmonic content due to the fixed timing of the PWM carrier was significant. At that time, the six-step technique, which is quite simple to control and requires power transistor switching rates equal only to twice the motor rotation frequency (times the number of motor pole pairs), were highly competitive with PWM inverters with respect to performance and cost. As PWM frequencies have increased and the control sophistication of PWM inverters has improved, the competitive position of PWM has improved considerably.

**Figure 5-6: Six Step Inverter Voltage and Current Wave Forms**



a) Voltage output of the three Inverter phases

b) Motor connections

c) Voltage wave form acros each winding

d) Current wave form each winding

Source: Lloyd, 1982

Efficiencies for six step inverters are about the same as for PWM inverters, perhaps one to two points lower. Efficiency of the drives decreases by one to two efficiency points as the size of the drive decreases because the control signal losses remain about the same. The output of these drives decreases the efficiency of the motor by about 10% compared to across the line AC voltage because the output current is noisy, and the six step waveform is only a crude approximation to a sinusoidal waveform and has significant higher harmonic content.

Table 5-3 shows current manufacturers, sizes, efficiencies, and costs of six step inverters. They are available from several sources, including Emerson, Lenze, and Boston Gear. They are available in sizes as small as 1/4 horsepower. Most six step inverters are marketed for fan, pump, and other industrial applications and provide features that appeal to this market.

**Table 5-3: Manufacturers of Six Step Inverters**

| Manufacturer | Size (hp) | Model (least power output) | Present Cost (quantity 1) |
|---|---|---|---|
| Lenze | 1/2 | 611 | 470 |
| Emerson | 1/2 | Horizon I | 3400 |
| Boston Gear | 1/4 | AFA 2100 C | 1,000 |
| Graham | | custom | 1,000 |

Source: Telephone conversations and/or product literature of the manufacturers listed.

### *5.4.4 Switched Reluctance Motors*

Switched reluctance motors are a relatively new technology, enabled by continuing improvements in power and control electronics technology. As shown in Figure 5-7, the motor consists of a rotor and stator, each having a different number of equally spaced discrete poles. The rotor consists of a stack of iron laminations with individual poles formed as shown in the Figure. There are no conductor bars and therefore no induced current in the rotor. The stator is formed from a stack of iron laminations, with individual, wound poles. The rotor position is sensed by an encoder in the motor housing and pulses of current are applied to the stator poles to match the rotor angle.

The pulses are timed, as indicated in the Figure, so that each stator pole is energized as a rotor pole approaches it, and deenergized when the rotor pole is aligned to it. The "generic" drive of Figure 5-2 is applicable, with PWM used to match the input voltage optimally to the speed and torque of the motor.

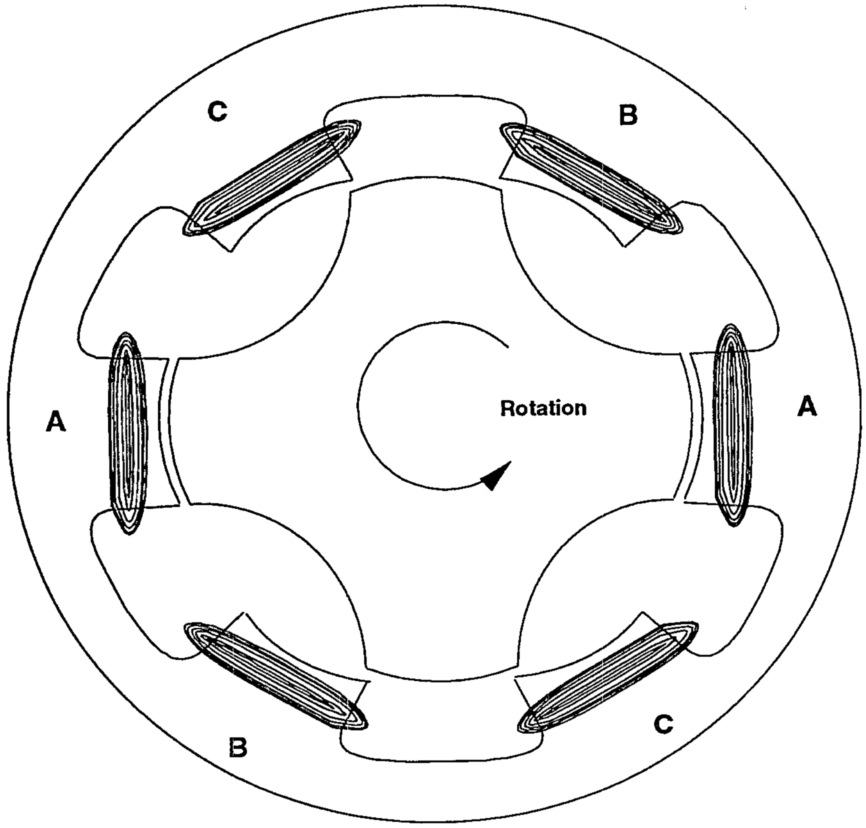
Switched reluctance motors have several unique attributes that are potentially advantageous, depending on the application:

- Very high low speed torque;
- The rotor uses no conductor bars or permanent magnets, and the potential cost of the motor is correspondingly lower;
- Overall motor/drive efficiency can approach ECPM motor/drive efficiency. However, to realize high efficiency requires very precise timing of energizing and deenergizing of the stator pole windings and very low loss (and high cost) lamination materials, limiting the potential cost benefits.

These features are not the distinguishing advantages for a refrigerator compressor motor that they are for vehicle traction drives or direct drives of washing machine agitators.

The technology was developed at Leeds and Nottingham Universities in England. Switched Reluctance Drives, Ltd. in Leeds, England licenses the technology. No U.S. manufacturer is in production of SRM's, but several development programs have been initiated in the U.S. SRM's are being investigated for use in electric vehicles for traction drives, where the characteristics high torque at low speed, (as needed for good acceleration), and good efficiency at higher speed and low torque (cruising conditions)

Figure 5-7: Simplified Schematic of Switched Reluctance Motor Configuration




At rotor position and rotation direction shown:

- Winding A has just been switched off
- Winding B is off
- Winding C was just switched on

of switched reluctance motors, as well as potentially lower motor costs, are key advantages. The Japanese are currently developing this technology for use with "quiet" washing machines. EPRI is also interested in this application; they are starting a project with Whirlpool and Emerson. In general, this technology is at an earlier stage of development and commercialization than the preceding three technologies.

## 6.0 Potential Value of Improvements

This report has examined three areas of motor technology

- Constant speed induction motors and the potential for their efficiency improvement
- Two speed motor technology
- Variable speed motor technology

The value of the efficiency improvements obtainable for single speed induction motors are considered in the compressor technology report (Dieckmann, 1991). The combination of increased cost and degraded efficiency associated with two speed induction motors in the fractional horsepower ranges leaves this a rather unattractive option for this application.

The potential system performance advantages of a variable speed compressor were examined parametrically, at the DOE closed door energy test condition, for the "typical" 18 cu ft. automatic frost free refrigerator/freezer with a top mounted freezer, as described in the Appendix. The cases considered were:

- 1993 standards level cabinet thermal performance, as a baseline, and a high performance cabinet (with 30% lower thermal loads).

- Current, fans and fan motors, and ECPM fans/motors.

- For the high performance cabinets, the basis for the single speed compressor capacity and maximum variable speed capacity was the capacity of the compressor in the typical 1993 R/F, reduced by half the decrease in cabinet load from current thermal performance, thereby maintaining pulldown capability.

- For each of the above cases, the performance with a single speed compressor was compared with the performance with a current technology variable speed motor - compressor and with a variable speed compressor having an efficient low speed range. The efficiency vs. speed characteristic of current technology variable speed drives was taken to be the upper, ECPM curve from Figure 5-4. The efficient low speed range drive was assumed to have a system efficiency of 84% at the low speeds where continuous steady state compressor operation would occur (30% of maximum speed; an efficiency of 84% is comparable to the one half speed efficiency of current technology drives).

Table 6-1 summarizes the energy savings for these cases that are attributable to replacing the single speed compressor with a variable speed compressor (current variable speed drive technology). The detailed underlying assumptions are presented in the Appendix.

Table 6-2 summarizes the energy savings for these cases that are attributable to replacing the single speed compressor with an efficient low speed variable speed compressor, as described above. The detailed underlying assumptions are presented in the Appendix.

**Table 6-1: Summary of Calculated Energy Savings with Variable Speed Compressor (Current Variable Speed Motor/Drive Technology)**

| Cabinet | Energy Consumption Single Speed kWh/yr | Fans | Energy Consumption kWh/yr | |
|---|---|---|---|---|
| | | | Variable Speed | Saving vs. Single Speed |
| Typical 1993 | 668 | Fan A | 665 | 3 |
| | 604 | Fan B | 510 | 94 |
| | 604 | Fan C | 485 | 119 |
| Low Thermal Loss w/Constant Pulldown | 452 | Fan A | 479 | -27 |
| | 402 | Fan B | 351 | 51 |
| | 402 | Fan C | 329 | 73 |

Fan A Standard fans, 1 speed
Fan B ECPM fans, 1 speed
Fan C ECPM variable speed condenser and evaporator fans

**Table 6-2: Summary of Calculated Energy Savings with Variable Speed Compressor (Efficient Low Speed -- Future Technology)**

| Cabinet | Energy Consumption Single Speed kWh/yr | Fans | Energy Consumption kWh/yr | |
|---|---|---|---|---|
| | | | Variable Speed | Saving vs. Single Speed |
| Typical 1993 | 668 | Fan A | 638 | 30 |
| | 604 | Fan B | 486 | 118 |
| | 604 | Fan C | 464 | 140 |
| Low Thermal Loss w/Constant Pulldown | 452 | Fan A | 460 | -8 |
| | 402 | Fan B | 334 | 68 |
| | 402 | Fan C | 313 | 89 |

Fan A Standard fans, 1 speed
Fan B ECPM fans, 1 speed
Fan C ECPM variable speed condenser and evaporator fans

The value of these energy savings is tabulated in Tables 6-3, and 6-4 assuming an electric energy cost of 8¢ per kWh, for a range of real discount rates between 2 and 10 percent, over the projected 15 year life of the refrigerator. The discount rates cover a range between real, after tax returns to savings accounts at the low end of the range, to after inflation credit card interest rates at the high end of the range. For real discount rates in the range that consumers would rationally choose for safe investments (at the low end of the range), the present value of the saved energy is on the order of $75 greater than the incremental cost, at retail, of the variable speed drive. The efficient low speed variable speed drive saves approximately 20 kWh/yr over current variable speed drive technology; the present value of the savings is approximately $20.

Table 6-3: **Present Value of Energy Savings of Variable to Speed Compressor (Current Variable Speed Motor/Drive Technology)**

| Cabinet | Fan | Savings kWh/yr | Present Value for Discount Rates | | |
|---|---|---|---|---|---|
| | | | 2% | 5% | 10% |
| Typical 1993 | A | 3 | 3 | 3 | 2 |
| | B | 94 | 98 | 81 | 60 |
| | C | 119 | 124 | 102 | 76 |
| Low Loss W/constant pulldown | A | -27 | -- | -- | -- |
| | B | 51 | 53 | 44 | 32 |
| | C | 73 | 76 | 63 | 46 |

- Electric energy cost $.08/kWh
- Over 15 year life of appliance
- Fan configuration: Table 6-1 footnotes

Table 6-4: **Present Value of Energy Savings of Variable to Speed Compressor (Efficient Low Speed -- Future Technology)**

| Cabinet | Fan | Savings kWh/yr | Present Value for Discount Rates | | |
|---|---|---|---|---|---|
| | | | 2% | 5% | 10% |
| Typical 1993 | A | 30 | 31 | 26 | 19 |
| | B | 118 | 123 | 101 | 75 |
| | C | 140 | 146 | 120 | 89 |
| Low Loss W/constant pulldown | A | -8 | -- | -- | -- |
| | B | 68 | 71 | 58 | 43 |
| | C | 89 | 93 | 76 | 57 |

- Electric energy cost $.08/kWh
- Over 15 year life of appliance
- Fan configuration: Table 6-1 footnotes

# 7.0 Areas for R & D

R & D resources could be applied usefully in two broad areas in motor technology: the development of higher efficiency induction motors for use in compressors, especially smaller compressors; and improvements in low speed performance of variable speed motors and drives while reducing costs.

The techniques for designing higher efficiency induction motors are well known in the hermetic motor industry. The major issues involved from the industry viewpoint are product engineering and marketing issues of cost vs. market size, and integration with the compressor. Because the motor is an integral part of the compressor package, high efficiency motor development is best carried out in the context of high efficiency compressor development. This subject, therefore, is discussed in greater length in the compressor technology report (Dieckmann, 1991) that was prepared under this program. Early development of small, high efficiency compressors would provide important support to current programs to demonstrate the performance potential of R/F's with dual loop systems and/or super insulated cabinets.

The results of the performance and payback analysis discussed in the Appendix and in Section 6, respectively, clearly indicate that significant energy savings can be obtained with variable speed compressors and fans. However, the savings are limited by the rapid degradation in variable speed drive (VSD) - motor efficiency below 50% of maximum speed. At current projected VSD - motor costs, the present value of the energy savings, at $0.08/kWh over the 15 year life of the R/F is only marginally greater than the likely increase in retail cost that would be needed to cover the incremental cost of the motor and drive. R&D efforts, therefore, should be targeted to:

- Increase the low speed (1/4 to 1/3 of maximum) VSD - motor efficiency, maximizing the savings that can be obtained with a variable speed compressor.

- Further efforts to reduce potential mass production costs, through increased component integration and utilization of advances in component technology.

- Prototype development of a variable speed compressor based R/F could be pursued, based on current technology, with detailed performance measurements providing a basis for further assessment of the potential of this approach and for identifying areas for improvement.

## 8.0 Conclusions

### 8.1 One Speed Motors (Present Practice)

2 pole AC squirrel cage induction motors running close to 3500 RPM and operating on 115 volts, 60 Hz, single phase AC are used universally in domestic refrigerator/freezers and freezers. In the small capacity compressors (< 600 Btu/hr nominal capacity) currently used in very small refrigerators, but potentially of interest for two compressor/two evaporator system designs, low cost, low efficiency motors are currently used.

Motors whose efficiency is very close (within 1 or 2 percentage points) to that of the motors used in the best domestic refrigerator compressors, with outputs matching the needs of smaller capacity compressors could be developed and manufactured fairly readily. The costs would be considerably higher than that of presently used motors -- cost benefit analyses are needed to determine the optimum efficiency. The cost-efficiency-power output data plotted in Figure 3-2 is reasonably accurate, and can be used in these trade-offs.

### 8.2 Two Speed Motors

As with one speed motors, the technology to design and produce two speed motors is well known. Two speed motors are inherently lower in efficiency than one speed motors of comparable cost, on a comparable mass production basis -- by several percentage points at maximum speed, and by close to 15 percentage points at half speed.

### 8.3 Variable Speed Drives

Inverter drives of induction motors and variable speed electronically commutated motor/drives are both well developed and commercialized technologies for providing a motor with continuously variable speed operation and control, although sales and production in the U.S. have not yet reached mass production levels for any application or class of applications. The latter is inherently higher in overall motor/drive efficiency by close to 15 percentage points, for the reasons discussed in 5.4.1 and 5.4.2. In mass produced configurations for domestic appliance applications, the costs of the electronic drives can be expected to be equivalent, while the permanent magnet motor is slightly higher in cost. The higher system efficiency of the electronically commuted motor and drive is well worth the small differential in cost.

Currently there is no large scale mass production of either type drive in the U.S. GE is marketing electronically commutated motors and drives targeted for mass market applications - appliance and automotive. Total unit sales of GE ECPM motor/drive systems are approaching 50,000 units annually, with rapid growth in unit sales coupled with steady decreases in unit costs. Inverters are mass produced in Japan, for applications such as small residential heat pumps. Manufacturing costs of these mass produced inverters are on the order of $100 per horsepower (over a range of 1 to 3 horsepower). As U.S. production quantities increase, costs can be expected to fall toward Japanese mass production cost levels.

The analyses in the Appendix and Section 6 indicate that at current real energy prices, the energy savings resulting from variable speed compressor operation are sufficient to payback the likely retail price differential that would result from the incremental manufacturing costs of applying a variable speed compressor to a typical R/F. The payback period is long, however; 5 to 10 years. One factor limiting the energy savings is the degradation of motor and system efficiency at the reduced speeds (about 1/4 to 1/3 of maximum) that would be typical of steady state operation.

## 9.0 References


Americold, 1990 (January), private communication.

Arthur D. Little, Inc., 1990 (August), "Impact of a CFC Ban on the Cost and Performance of Household Refrigerators, Centrifugal Chillers, and Commercial/Industrial Refrigertion Systems," Technical Memorandum to U.S. DOE.

Baldor, 1989 (November), private communication.

Cann, P., 1989 (November 28 - December 1), "Integrated Heat Pumps", Meeting Customer Needs with Heat Pumps. Atlanta, GA., Sponsored by EPRI.

Copeland, 1990 (January), private communication.

Dieckmann, J.T., 1991, State of the Art Survey of Hermetic Compressor Technology Applicable to Domestic Refrigerator/Freezers, report to EPA Global Change Division, prepared by Arthur D. Little, Inc., Cambridge, MA.

Electric Power Research Institute, 1987, "ASD Directory," Second Edition, Palo Alto, California.

Emerson Electric, 1990 (January), private communication.

Federal Register, 1989a (February 7), pp. 6077 - 8.

Federal Register, 1989b (November 17), pp. 47916 - 47938.

GE Motors, 1990a (January 12), Telefax summarizing induction motor efficiencies.

GE Motors, 1990b (January), private communication.

Greenberg, S., et al., 1988, Technology Assessment: Adjustable Speed Motors and Motor Drives (Residential and Commercial Sectors), LBL-25080.

Lloyd, J. D., 1982, Variable - Speed Compressor Motors operated on Inverters, AHSRAE Transactions V88, pt 1.

Lorenz, A., Meutzner, K., 1975, "On Application of Non-azeotropic Two-component Refrigerants in Domestic Refrigerators and Home Freezers," IIR.

Lovins, A. B., et al., 1989 Edition (April), The State of the Art: Drivepower, Rocky Mountain Institute, Snowmass, CO.

Smith, A.O., 1990 (January), private communication.

Sulfstede, L., 1989 (November 28 - December 1), "Residential Variable Speed Technology." Meeting Customer Needs with Heat Pumps, Atlanta, GA., Sponsored by EPRI.

Toshiba(a) International Corporation, Houston, Texas, Toshiba Instruction and Maintenance Manual - Tosvert - 130E Transistor Inverter. Bulletin No. IMVT130E230.

Toshiba(b) International Corporation, Houston, Texas, Toshiba Inverter Seminar (a 20 page brochure published by Toshiba).

## Appendix: Value of Variable Speed Motors for Reducing Cycling Losses, and Otherwise Improving R/F Efficiency

One basic premise underlying the variable speed motor state of the art survey is that the potential exists to obtain significant energy savings with an efficient variable speed compressor. The primary sources of the savings are the elimination of losses associated with on-off cycles, improved utilization of heat exchanger capacity, and, possibly, savings in fan power if fans were operated at reduced speed (taking advantage of the speed cubed fan power law) when the compressor speed is reduced. To examine this basic premise, a series of comparative performance calculations were carried out, at the standard DOE closed door energy test conditions, using the EPA refrigeration analysis (ERA) model. As indicated in Table A-1, the main points of comparison are:

- Constant speed vs. continuously variable speed (e.g. cyclic operation vs. continuous),
- Effect of (importance of) fan efficiency,
- For a variable speed compressor, constant speed ECPM fans vs. variable speed ECPM fans operated at reduced speed and substantially reduced power.

**Table A-1: Matrix of Constant Speed vs. Variable Speed Cases**

| Cabinet | Fans w/Single Speed | Fans w/Variable Speed |
|---|---|---|
| Baseline | Standard Efficiency | Standard Efficiency |
| | ECPM, 1 Speed | ECPM, 1 Speed |
| | ECPM, 1 speed | ECPM, Variable Speed |
| High Performance | Standard Efficiency | Standard Efficiency |
| (Thermal load 2/3 of baseline) | ECPM, 1 Speed | ECPM, 1 Speed |
| | ECPM, 1 Speed | ECPM, Variable Speed |

To obtain meaningful results on the comparative effects of variable speed and different fan efficiency levels, the following assumptions were followed for all cases:

- The baseline R/F is an 18 cubic foot refrigerator freezer with automatic defrost and a top mounted freezer, having freezer wall insulation 2 3/8 inch thick and fresh food compartment insulation 1 7/8 inch thick (R value 8.0 °F/in per Btu/hr-ft$^2$). The annual DOE test energy use is approximately 20 kWh/yr over the 1993 standard level (668 kWh/year vs. a 1993 standard level of 690 kWh/year). The freezer volume is 4.6 cubic feet and the refrigerator volume is 13.4 cubic feet; the adjusted volume is 20.9 cubic feet.

- The baseline compressor has a nominal EER of 5.3 and a nominal capacity of 865 Btu/hr.

- Losses associated with on-off cycling of the constant speed compressor are assumed to add 2% to the compressor input power at a 50 percent duty cycle.

- The ECPM compressor motor has about a 13% efficiency advantage over the baseline unit, including electronics losses, at constant speed.

- The current technology variable speed motor and drive system efficiency-speed relationship is assumed to be as shown in Figure 5-4 for electronically commutated permanent magnet rotor (ECPM) motors. At maximum speed about 1/3 of the losses (3% of the total input power) occur in the drive electronics, and the remainder (7% of the total input power) occur in the motor. At lower speeds, a higher proportion of the losses occur in the electronics.

- The "efficient low speed" variable speed drive is assumed to have an overall system efficiency of 84% at 25% to 30% of maximum speed, comparable to the half speed efficiency of current technology variable speed drives. 25% to 33% of maximum speed is the steady state speed range that results when the compressor is sized to provide pulldown performance comparable to current R/F. This level of low speed variable speed drive performance is not currently available, but could potentially be achieved through R&D.

- At 30% speed, assumed to be the lowest practical speed that will ensure proper lubrication, the compressor motor drops efficiency 10% from the maximum speed value, including electronics losses.

- The baseline steady state cabinet loads are 134 Btu/hr (fresh food compartment) and 135 Btu/hr (freezer), including the effect of mullion heaters and controls, but not the power input to the evaporator fan, which varies with duty cycle and fan efficiency.

- The baseline condenser fan moves 90 ACFM through the condenser, and its motor consumes 12 watts.

- The baseline evaporator fan moves 50 ACFM through the evaporator, and its motor consumes 9.4 watts.

- ECPM constant speed fans are assumed to move the same air flow as the baseline, with 3.6 watts power input to the motor.

- The effect of variable speed refrigerant mass flow and fan air flow on heat exchanger performance is estimated using the heat exchanger routines within ERA.

- The "high performance" cabinet is assumed to have 70% of the steady state conduction load as the baseline cabinet. This level of cabinet performance, combined with refrigeration cycle improvements, would result in energy consumption approaching the DOE "Level 5". The design measures to achieve this reduction aren't specified for this study, but could include thicker walls, improved door gaskets, carbon black insulation, and reduced anti-sweat heat. Pulldown requirements are assumed to be identical. Therefore, the nominal compressor capacity (maximum capacity for variable speed) is taken to be 85% of the baseline cabinet compressor capacity.

- Fan powers and air flow rates are unscaled, i.e., equal to the baseline cabinet case.

Tables A-2 and A-3 summarize the results of the efficiency comparison, for the baseline cabinet and for the high performance cabinet. The major observations relative to these results are:

- A substantial energy saving (10%) can be obtained by replacing the inefficient fan/motor of typical current practice with a modest efficiency fan and motor.

- With the standard efficiency fan/motor, the variable speed drive operating at steady state does not result in energy savings since the energy associated with 100% fan run time more than offsets the compressor power savings.

- With ECPM fans, the VSD compressor results in a substantial net energy savings.

- A limitation on the compressor energy savings is the declining variable speed motor system efficiency below half speed (using current technology). The last three cases of Tables A-2 and A-3 are based on an assumed variable speed motor drive system efficiency of 84% at 30% of nominal speed (vs. 90% at maximum speed and 84% at one half speed, with current technology). For this improved level of low speed motor performance, energy use is reduced by approximately 25 kWh/year over the comparable, current variable speed technology case.

- The same general observations apply to the high performance cabinet, with increased sensitivity of the variable speed options to the fan efficiency.

Table A-2: Calculated Results - Standard Cabinets

| Case | Fan Watts | | Cabinet[1] Load Inc. Fan BtuH | Duty Cycle / % Speed | Energy Inputs, kWh/day | | | | Total Energy kWh/yr |
|---|---|---|---|---|---|---|---|---|---|
| | Evap. | Cond. | | | Comp.[2] | Fans | Aux.[3] | Total | |
| Baseline | 9.4 | 12.0 | 280 | .38 | 1.49 | .20 | .15 | 1.83 | 668 |
| Constant Speed and ECPM Fans | 3.6 | 3.6 | 273 | .37 | 1.44 | .06 | .15 | 1.66 | 604 |
| ECPM at Full Speed, Standard Fans | 9.4 | 12.0 | 280 | .37 | 1.28 | .19 | .15 | 1.62 | 591 |
| ECPM at Full Speed, ECPM Fans | 3.6 | 3.6 | 273 | .36 | 1.25 | .06 | .15 | 1.46 | 531 |
| Variable Speed and Standard Fans | 9.4 | 12.0 | 299 | .98 / 30% | 1.17 | .50 | .15 | 1.82 | 665 |
| Variable Speed ECPM Fans | 3.6 | 3.6 | 279 | .90 / 30 | 1.09 | .16 | .15 | 1.40 | 510 |
| Variable Speed Variable sp. Fans[4] | 2.0 | 2.0 | 274 | .91 / 30% | 1.09 | .09 | .15 | 1.33 | 485 |
| Efficient Low Speed Variable Speed/Std Fans | 9.4 | 12.0 | 299 | .97 / 30% | 1.10 | .50 | .15 | 1.75 | 638 |
| Efficient Low Speed Variable Speed and ECPM Fans | 3.6 | 3.6 | 279 | .90 / 30% | 1.03 | .16 | .15 | 1.33 | 486 |
| Efficient Low Speed Variable Speed and ECPM Fans | 2.0 | 2.0 | 274 | .90 / 30% | 1.03 | .09 | .15 | 1.27 | 464 |

(1) Base cabinet load except fans = 268 Btu/hr
(2) Incl. 2% for on-off cycling loss constant speed
(3) Aux: controls, defrost, anti-sweat heaters
(4) Fans at 83% speed, 83% air flow

Table A-3: Calculated Results - High Performance Cabinet

| Case | Fan Watts | | Cabinet[1] Load Incl. Fan, BtuH | Duty Cycle / % Speed[2] | Energy Inputs, kWh/day | | | | Total Energy kWh/yr |
|---|---|---|---|---|---|---|---|---|---|
| | Evap. | Cond. | | | Comp.[3] | Fans | Aux.[4] | Total | |
| Baseline | 9.4 | 12.0 | 200 | .30 | 1.01 | .16 | .07 | 1.24 | 452 |
| Constant Speed and ECPM Fans | 3.6 | 3.6 | 194 | .29 | 0.98 | .05 | .07 | 1.10 | 402 |
| ECPM at Full Speed, Standard Fans | 9.4 | 12.0 | 200 | .30 | .87 | .15 | .07 | 1.10 | 400 |
| ECPM at Full Speed, ECPM Fans | 3.6 | 3.6 | 194 | .29 | .84 | .05 | .07 | .97 | 353 |
| Variable Speed and Standard Fans | 9.4 | 12.0 | 216 | .81 / 30% | .82 | .42 | .07 | 1.31 | 479 |
| Variable Speed ECPM Fans | 3.6 | 3.6 | 199 | .74 / 30% | .76 | .13 | .07 | .96 | 351 |
| Variable Speed Variable sp. Fans[5] | 2.0 | 2.0 | 195 | .74 / 30% | .76 | .07 | .07 | .90 | 329 |
| Efficient Low Speed Variable Speed and Standard Fans | 9.4 | 12.0 | 216 | .80 / 30% | .78 | .41 | .07 | 1.26 | 460 |
| Efficient Low Speed Variable Speed and ECPM Fans | 3.6 | 3.6 | 199 | .74 / 30% | .72 | .13 | .07 | .92 | 334 |
| Efficient Low Speed Variable Speed and Variable Speed Fans | 2.0 | 2.0 | 195 | .73 / 30% | .71 | .07 | .07 | .86 | 313 |

(1) Base cabinet load less fans = 190 Btu/hr
(2) Baseline case compressor capacity 735 Btu/hr
(3) Incl 2% for on-off cycle losses of 1 speed compressor
(4) Auxiliary: controls, defrost, anti-sweat heaters
(5) Fans at 83% speed, 83% air flow